Design and manufacture of the DEMON unmanned air vehicle demonstrator vehicle

J P Fielding*, **A Mills,** and **H Smith**
Department of Aerospace Engineering and School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, UK

The manuscript was received on 18 June 2009 and was accepted after revision for publication on 15 September 2009.

DOI: 10.1243/09544100JAERO645

Abstract: This article will describe the design process, final design, and manufacture of the DEMON unmanned air vehicle (UAV) flying demonstrator aircraft. This is one of the main activities of the multi-University FLAVIIR programme.

FLAVIIR's aim is to develop technologies that will allow development of future UAVs. It is vital that these technologies be integrated and demonstrated at higher technology readiness levels than are usual in the University sector. One means of achieving this is to use a number of technology demonstrators, culminating in the DEMON demonstrator. A particularly challenging requirement is that the vehicle must demonstrate an entire flight cycle, without the use of conventional flying control surfaces.

This article will describe some of the technologies developed by partner Universities, and their integration into DEMON.

The vehicle has a novel configuration and uses advanced composite construction in a vehicle some 3 m long and weighing 80 kg. It is powered by a small gas turbine and utilizes sophisticated thrust-vectoring devices. A novel feature is the use of an auxiliary gas turbine that provides compressed air for some of the fluidic control devices.

This article gives details of the innovative manufacturing and assembly methods used for the DEMON. The vehicle is expected to fly shortly.

Keywords: advanced flight control, flight demonstration, fluidic devices, low-cost composite structure, unmanned air vehicle

1 INTRODUCTION

Fielding and Smith [**1**] gave an introduction to the origins of the FLAVIIR programme, which is investigating a wide range of technologies, applicable to improvements in future unmanned air vehicle (UAV) systems.

It was recognized that such technologies could have individual merit, but that integrated together could have synergistic benefits. It was also realized that while such technologies might be considered to be attractive during theoretical, computational, or bench-test phases, they may be unworkable in realistic operating environments. It was, therefore, decided that the FLAVIIR programme needed a significant integration and demonstrator element, to be led by Cranfield University. A number of demonstrator activities were performed, which will cumulate in flight tests of a representative UAV demonstrator vehicle, which will incorporate as many FLAVIIR technologies as possible.

This activity has the important function of enhancing the integration of research efforts from a number of Universities and fostering collaboration between them and the sponsoring company, BAESYSTEMS.

2 DEMONSTRATION AND VEHICLE REQUREMENTS

2.1 Aims

The overall FLAVIIR project aims were summarized in reference [**1**] as follows.

Challenge 1: to develop technologies for low-cost, maintenance-free UAV without conventional control surfaces and without performance penalty.

*Corresponding author: Department of Aerospace Engineering and School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK.
email: j.p.fielding@cranfield.ac.uk*

Challenge 2: significant research impact through academic/industry management and exploitation of large-scale integrated academic research.

To support these overall aims, the demonstration aims included the needs to:

(a) demonstrate technologies in a realistic airborne environment;
(b) integrate the technologies into a working flying vehicle;
(c) demonstrate technology readiness levels higher than normal University programmes, preferably up to 4 or 5;
(d) to provide means for industrial exploitation;
(e) provide research about the integration process.

2.2 Vehicle requirements and initial design

2.2.1 *Flight performance*

The vehicle will demonstrate a full flight cycle from take-off to landing without the use of conventional flight control surfaces.

The aircraft will operate from airfields with manoeuvres that will ensure that the aircraft altitude will not exceed 400 ft and distance from the pilot of more than 500 m.

Initial manoeuvres will demonstrate the capability of performing racetrack or figure of eight manoeuvres. Subsequent flights will demonstrate completely autonomous flight.

2.2.2 *Airworthiness requirements*

The aircraft will be safe to operate and will be demonstrated to comply with reference [**2**] 'over 20 kg' category. Where appropriate, the vehicle will be designed to EASA-VLA requirements.

2.2.3 *Costs and timescales*

The vehicle will be designed, manufactured, and flown within the original budget of the FLAVIIR Programme, and performs flight tests in the fifth year of the programme.

2.2.4 *Initial design decisions*

The aims, requirements and budget for the vehicle were seen to be extremely challenging. It was therefore, decided to examine several previous Cranfield University-designed and built UAVs with the view to utilize many of their design features, and thus minimizes design and development effort. Reference [**3**] discussed the aircraft that were considered and the early development process for the ECLIPSE vehicle (Fig. 1).

The original intention was to use as much as possible of the ECLIPSE design and configuration, together with the integration of many FLAVIIR technologies, in particular, the fluidic thrust vectoring (FTV) system being developed by Manchester University and fluidic circulation control devices (CCD) being developed by Manchester and Cranfield Universities.

Fig. 1 The Eclipse vehicle performing taxi trials

It was decided to construct the airframe from low-risk and low-cost conventional pre-preg carbon-fibre construction. The design would be oriented towards robustness and to have the flexibility to cater for future developments within and beyond the FLAVIIR programme.

3 CONCEPTUAL AND PRELIMINARY DESIGN

3.1 Initial modifications to the Eclipse configuration

The Eclipse utilizes four trailing-edge devices per wing and initial performance, stability, and control analyses showed that adequate role control could be provided by replacing the inboard aileron flap with a CCD in each wing.

The FTV system required a two-dimensional nozzle and so the rear fuselage was re-shaped to accommodate this, although the original AMT Olympus engine was retained. It was realized that a secondary air supply would be needed to provide relatively high-pressure air for the CCDs. The secondary air was to be provided by bleeding air from the aircraft engine or by other means.

The original flight control system (FCS) hardware of the Eclipse was obsolete, large, and heavy. This was to be replaced by a lighter, smaller unit. It was also decided to give the aircraft a longitudinal static stability margin of some 3 per cent, to allow for remotely-piloted operation of the aircraft. The smaller FCS allowed the forward fuselage to be used as a payload bay or to provide space for a secondary air supply system. Figure 2 shows a CAD model, highlighting the CC devices, thrust vectoring nozzle, and the initial air supply from a pressurized reservoir. It was later decided to replace this with a small model gas

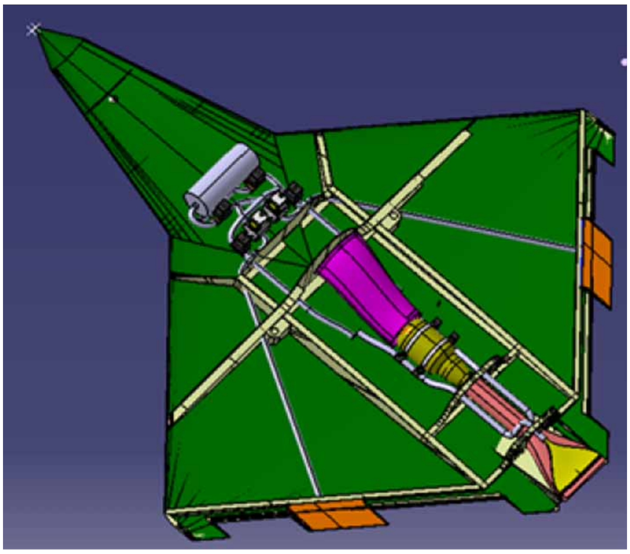

Fig. 2 Schematic of the original Demon configuration

turbine, driving a compressor to provide air for the CC devices. This was referred to as an auxiliary power unit (APU).

3.2 Aerodynamic analyses

Lift, drag, and performance calculations were performed for the modified Eclipse vehicle, which was re-named DEMON. Considerable effort was expended on wind-tunnel tests. A half-scale Eclipse model was tested in the Cranfield 8×6 ft wind tunnel. These results compared favourably with the earlier simple Eclipse wind-tunnel and empirical data sheet prediction methods. The model was then modified to incorporate the new rear fuselage shape required for DEMON's thrust-vectoring system (Fig. 3).

Parallel wind-tunnel tests were performed with an articulated flight-dynamics wind-tunnel model by Cranfield's Aerodynamics group and a powered half-model by Manchester University. The results were fed into a sophisticated flight control model that was tested by experienced UAV pilots in BAESYSTEMS' flight simulation facility. Control and handling were found to be suitable for the required flight manoeuvres.

3.3 Structures and systems conceptual design

It was decided to use a multi-spar structural design for the wing. This released internal volume for use by the air-pipes used to feed the CC devices. It was decided to use a fixed landing gear and to redesign it to allow for increased take-off mass of the DEMON relative to the Eclipse. Most of the Eclipse systems were retained including the power plant installation, but modifications were made for the new nozzle and APU, as described above.

3.4 Increase of size to the DEMON 115

The advanced technology systems required considerable space in the original Demon airframe, so it was decided to implement a 15 per cent linear increase in size of the airframe, keeping the same shape to retain the proven aerodynamic data. This gave a significant increase in internal volume that gave payload flexibility.

4 ECLIPSE DEVELOPMENT AND TAXI TRIALS

Flight demonstration inevitably involves considerable risk, so it was decided to modify the previously mentioned Cranfield Eclipse UAV to investigate critical design areas, prior to the detailed design of the similarly shaped but larger and heavier Demon aircraft.

This process is described in reference [**4**], and briefly discussed here.

The major modifications to the Eclipse were the replacement of the previous flight control system by a Weatronic/FUTABA radio-controlled flight control system and an Eagle Tree telemetry system. Wiring and pipework were replaced. Nose and main landing gear units were modified, as was the pneumatic system. Ballast was installed in the aircraft's nose to allow variations in aircraft stability to be explored. Figure 4 shows some details of the aircraft's nose section.

It was originally intended to perform flight tests of the aircraft, in conjunction with trials of other UAVs but this was not possible, due to cost and timescale issues.

However, the aircraft was completed and performed low-speed and mid-speed taxi trials, which provided

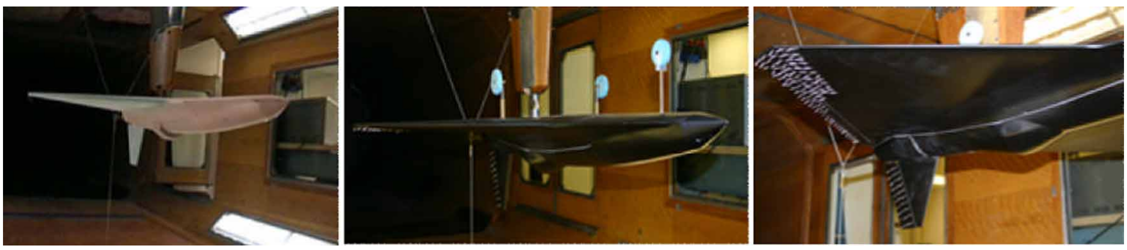

Fig. 3 Half-scale Demon wind-tunnel tests

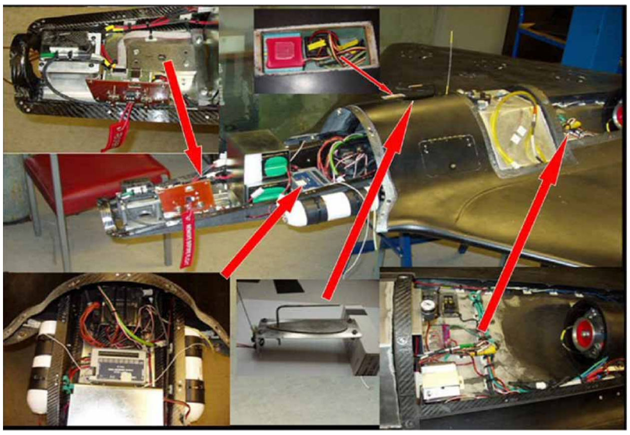

Fig. 4 Major systems in the nose of the Eclipse vehicle

much useful information. This included shake-down trials of all systems, which proved that their integration was successful. It highlighted minor deficiencies of the fuel system which have been remedied in the Demon aircraft. The braking and landing gear systems were inadequate and this experience has led to the significant improvements that have been incorporated in the DEMON landing gear.

5 DEMON DETAIL DESIGN AND MANUFACTURE

5.1 Detail design process

As the vehicle design progressed to detail design, more information became available, and helped to progress the vehicle design.

The requirement for the demonstration of flapless flight was found to be extremely difficult during approach and landing. The FTV system was shown to be suitable for take-off and cruise but lacked sufficient pitch authority at the reduced throttle settings required for approach and landing.

It was, therefore, decided to provide a source of secondary air flow in addition to the engine bleed source used for the FTV system. This will be used to power the additional, inboard, circulation-controlled pitch devices, as well as the outer CC devices. The secondary air supply system is provided by a small APU, driving an air compressor, as mentioned above (Fig. 5).

These changes led to weight growth, as in most aircraft development programmes. This tendency was aggravated by the aft centre of gravity tendency of rear fuselage-mounted engines combined with a thrust vectoring system. It had been decided to provide the aircraft with a positive static margin and, therefore, nose ballast was required, thus aggravating weight growth.

This situation was mitigated by careful repositioning of heavier components towards the nose of the aircraft and selection of a lighter FCS and attention to detail weight saving.

Fig. 5 APU/compressor unit for the Demon

The aircraft was still some 5 kg overweight and concerns were expressed about the installed thrust of the AMT Olympus engine. It was decided to replace it with the slightly larger TITAN engine with an uninstalled thrust of 390 N. This will give suitable thrust margins for the aircraft, but at a small engine mass increase and increase in fuel consumption.

The mass, centre of gravity, and performance have stabilized and will allow the aircraft to fly the required experimental flights at all-up masses of 80 kg.

5.2 DEMON vehicle description

Figure 6 shows a current CAD model of the aircraft internal layout. Of particular note are the FTV and CC devices that are being developed by Manchester University and built by the Apprentice School of BAE SYSTEMS. The APU and compressor system have been designed and constructed by WREN turbines and the flight control system by Bluebear Systems Research. Advanced flight control algorithms are being developed by Leicester University and Imperial College, and will be installed in the FCS and flight-tested during the second phase of flight tests. The aircraft design, integration, alternative CC devices, and airframe manufacture are being performed by Cranfield University.

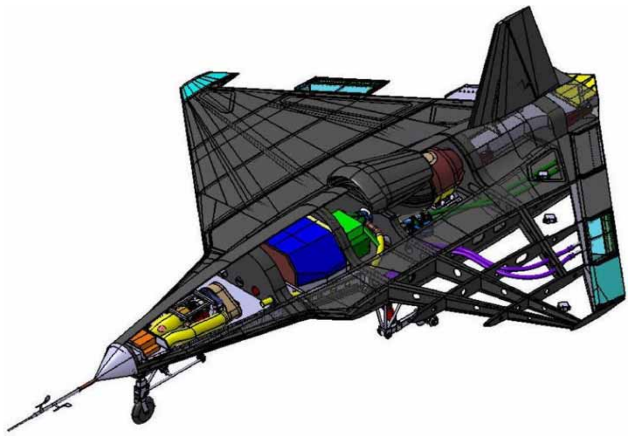

Fig. 6 CAD model of the final Demon vehicle

Fig. 7 Woven pre-preg ply being laminated onto film adhesive covering

Fig. 8 Adhesive applied to spar upper flanges before upper fuselage skin bonding

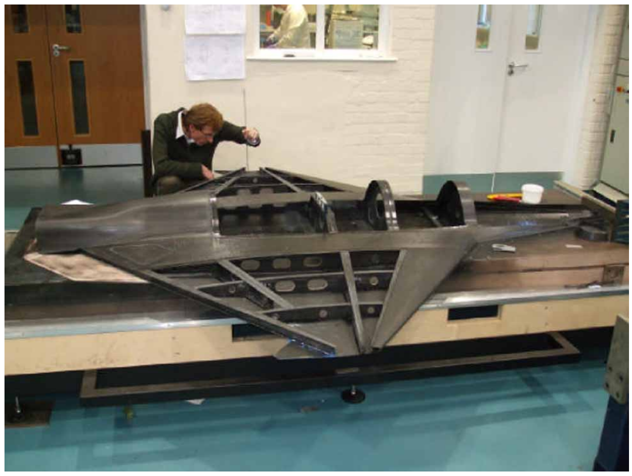

Fig. 9 First stage bonding complete

A conventional fin and rudder will be used during the first series of flight tests, but alternative systems are being investigated.

Figures 7 to 9 show photographs of the vehicle's carbon-fibre structural assembly.

5.3 Carbon-fibre structure manufacture

The driving requirements for the airframe manufacture were weight and tooling cost minimization. How these were addressed are discussed in sections 5.3.1 to 5.3.5.

5.3.1 Materials

The most effective carbon fibre composite (CFC) reinforcement materials for very light weight, thin, but highly curved structures are a combination of materials. Bi-axial woven fabric, which can easily drape to conform to complex double curvature surfaces without wrinkling and unidirectional tape, added to woven fabric in single curvature areas requiring maximum stiffness. For Demon the complete structure used biaxial fabric with strips of unidirectional tape laminated between fabric layers in all of the spar flanges. All fabric and tape was specified as 0.25 mm thickness to provide a good balance between thickness tailoring and lay-up time. Thinner fabrics and tapes are available, which allow more precise thickness tailoring, but their laminating time is very high since they require more layers and are vulnerable to distortion and wrinkling during laminating. Fabrics pre-impregnated with epoxy resin with a cure temperature of 5–10 °C were specified throughout, supplied by the Advanced Composites Group (ACG) (type LTM 26 EL; Derby, UK), these pre-preg materials eliminate the need to apply resin by hand and provide a precise and minimized resin content throughout the structure and hence are very effective for weight saving. The LTM ranges are cured at unusually low temperatures for extended times, thereby allowing the use of low-cost tooling material. CFC has a very low coefficient of thermal expansion and the final dimensions of the component are set by the tooling expansion at the maximum temperature of the cure. Hence, the use of minimum temperature curing greatly reduces the dimensional tolerance compensation required compared to curing at the standard series production pre-preg temperature of 12 °C. The LTM 26EL type has the lowest cure temperature of minimum 5 °C, but has the associated disadvantage that the pre-preg has a maximum laminating time, the out of freezer storage life of 6 days. This necessitates very strict pre-preg storage and fast laminating. Both pre-pregs have a higher resin content than series production materials of 40–42 per cent, which results in a laminate fibre volume fraction of around 50 per cent. This allows oven curing, with only vacuum bag pressure to be used.

For the fuselage skin and access panel sandwich components, 2 ply 0.5 mm thickness skins either side of 5 mm low density (30 kg m^{-3}) Nomex (phenolic-resin-coated aramid paper) honeycomb core, supplied by Hexcel Composites (Cambridge, UK) was selected to minimize weight.

5.3.2 Tooling

For a single demonstrator airframe, mould tool cost is a major part of the overall manufacturing cost, especially with very light structure. Series production standard tooling would be manufactured by the computer numerically controlled (CNC) machining of epoxy tooling block patterns, then laminating with carbon fibre fabric epoxy resin pre-preg and autoclave curing. For the Demon, this would have cost over £150 000, around 70 times the cost of the materials used to manufacture the airframe. Consequently, minimum cost routes were selected. Three types of tooling were used: for the nearly flat components, the wing skins, and the shallow leading edges, CNC machining of aluminium plate was selected. For the very large, heavy fuselage skin tools, CNC machined low-cost polyurethane-based tooling block (effectively a moisture insensitive replacement for wood). For the complex shape I beam spars and ribs, where precise flange radii are required, an epoxy-based, higher strength version of tooling block was used. All tools were hand rubbed to 600 grit emery paper finish and coated with Amber Composites EC85 surface sealant and then with Amber Marbocote RS415 and 220 release agent.

5.3.3 Moulding

The part geometry allowed standard lay-up techniques for all components except the spars. To fit the engine and control systems with minimal complication, the four wing tip to wing tip I section spars had been designed with two kinks.

Since the I section spars provide most of the airframe strength and stiffness for the wing loading, it was critical that the flanges were manufactured to provide complete load transfer across the kink. Conventionally this is achieved by breaking the spars into sections and bolting metallic fittings to each part. For a one off demonstrator, the design, assembly fixture, and machining costs for these very complex parts is excessive and so a complex lay-up to ensure strength carry through in the tension and compression load carrying flanges from spar tip to tip was defined. Adjacent to the kink, the woven and unidirectional plies were cut to butt up precisely in each layer to avoid overlap and hence fibre kinking, with each layer joint being staggered through the flange thickness by greater than 10 mm to maintain the strength. The I section spars were adhesively bonded from two separately moulded C sections.

All pre-pregs were hand cut and laminated, then prepared for oven cure using the following consumable layers. Electrically (not flouropolymer) treated peel ply against the upper surface to prepare for bonding, pin prick fluorinated ethylene propylene release film to allow air and volatiles to escape the pre-preg with the applied bag vacuum pressure, polyester breather blanket to remove the air and volatiles to the vacuum pump, and polyamide vacuum bagging film to seal the tool and apply vacuum pressure. A vacuum was applied to at least 15 mbar and then the laminate was cured in a fan oven at 5 °C for 20 h. The fuselage skin tools were too large and heavy for oven cure in the University labs and so an oven was constructed from PU foam sheet, aluminium foil house building floor insulation sheet, and two fan heaters. The sandwich structures additionally needed film adhesive to ensure sufficient bond strength of the facing skins to the core (see Fig. 7). A pre-preg compatible film adhesive, LTA 26 EL at 0.3 mm thick from ACG, was selected after lay-up trials showed that thinner films could not be draped over the pre-preg without folding and tearing. All parts were moulded at least 5 mm over size, then trimmed to final dimension using a diamond-coated cutting disc, and then hand smoothed by emery paper.

5.3.4 Assembly

With pre-preg manufacture using single-sided tooling, the inner, non-tooled surface is produced by the compression of soft fabric layers, which produces a wrinkled surface, has both variable thicknesses, and is uneven. Consequently, unlike machined aluminium components, there is very poor component fit and most parts need to be held in position during adhesive curing. The fuselage upper and lower sections are self-jigged since the upper and lower fit together with an overlapped (joggled) joint and 90° flanges pressed onto a flat surface. The wing assembly needs the spars to be jigged during bonding. The critical dimensions were identified as wing height and sweep, and so an assembly jig was designed to ensure that the front and rear main spars were bonded accurately to the lower skin. This would ensure that the leading edges would fit between the spars and the fuselage and the rear spar control devices would be precisely located.

A jig with accurately located side and end rails was fitted to the lower fuselage tool, levelled in both planes, and the lower skin aligned. The spars were jigged and clamped in position first dry and then with applied adhesive, before leaving for cure, the spar flanges and rules placed over the spar cap longitudinally were checked by spirit level. After spar to lower skin bonding, the root rib sections were bonded to the edge of the lower skin in between the spars. The lower wing skins were aligned with the spars and bonded to the spar caps, then the four sets of mid rib sections were bonded to the lower wing skin. The leading edges were then bonded to the lower fuselage skin, front spar flanges, and front rib sections. The final and most anxious stage of the initial assembly was the fitting of the upper fuselage. Having such a large bonding area with relatively stiff adhesive requires considerable load to close the joints. This was applied using both adhesive tapes to hold the front section to the lower fuselage, while 10 kg weights were applied to the panel over each spar after hand pressing the panel to fit (see Fig. 8).

The adhesive used was at room temperature curing two-part epoxy, Huntsman Redux 420 in three forms. For close fitting parts, as mixed with no thickening, for gap filling in highly loaded areas, such as the upper fuselage to spar caps, the adhesive was mixed with cotton flock as a crack stopper and a thickening silica powder. For filling gaps after the initial bonding, the mixed adhesive had added silica. Without the silica powder, the adhesive cannot fill a large or vertical surface gap, but flows away from the joint. The total mass of paste adhesive used in the assembly was 700 g.

5.3.5 Validation

To ensure that the pre-preg and film adhesives were fully cured, test coupons were manufactured ahead of the build. Single skin and honeycomb core/double skin coupons were placed in an oven at 8 °C supported at each end to check for resin or adhesive softening. Sandwich coupons were unpeeled to assess skin adhesive strength. The paste adhesives were checked by storing a sample from each bonding stage and checking final hardness with a knife blade.

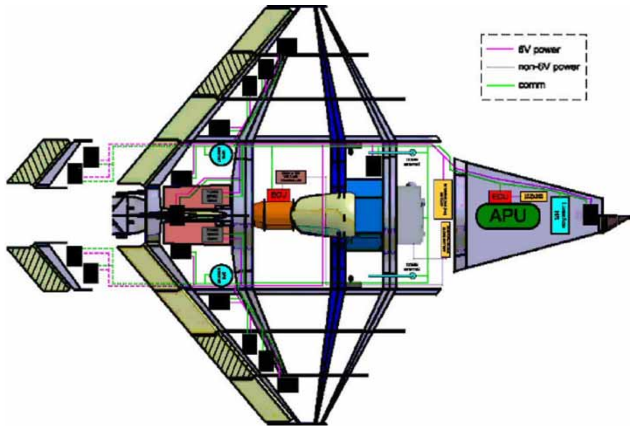

Fig. 10 Demon electrical installation

The first stage bonding critical dimensions were assessed by measuring the wing skin tip and spar tip positions. The lower wing skin tip height left and right were within ±1 mm. The spar web tip positions from the fuselage skin front edge were within ±1.5 mm (see Fig. 9).

The total mass of the airframe structure, excluding the removable fin, ailerons, and wing tips is 18.5 kg, which is around 0.5 kg less than estimated at the design stage.

5.4 Metallic structure and systems installations

The forward fuselage payload bay floor is being constructed from aluminium alloy and will provide locations for the nose landing gear APU, batteries, and ballast.

The aircraft secondary power is provided by a number of batteries fitted in the nose of the aircraft, to minimize ballast requirements. Figure 10 shows the location of the main electrical components, including a large number of actuators.

6 FUTURE ACTIVITIES

Several component and system test rigs have been completed and are being used. Initial trials of the propulsion rig have shown promising results, as have those for the APU/Compressor rig. Metallic structural components are being manufactured and the landing-gear will be examined using the drop-test rig.

A pneumatic system rig is being developed. The systems will then be installed in the vehicle and systems and structural tests will be performed, prior to a series of flight tests, in the Autumn of 2009. Such tests should validate the separate and integrated FLAVIIR technologies and meet the requirements of the programme. It is hoped that the flexibility of the DEMON design will allow it to be used for research activities after the conclusion of the FLAVIIR project.

7 CONCLUSIONS

1. The Eclipse UAV taxi trials have been valuable activities. They have evaluated sub-systems to be used in to the DEMON vehicle as well as highlighting improvements required for the new aircraft.
2. The current status of the DEMON vehicle is that detail design is complete and has led to a vehicle with mass and performance capable of meeting, or exceeding requirements.
3. Many sub-system rigs and test facilities have been made and successful testing has been performed. The engine and APU/compressor have been acquired and successfully tested.
4. The airframe manufacture is virtually complete and is meeting mass targets.
5. There is great confidence that the aircraft will be able to fly shortly and meet the objectives set for it.
6. The DEMON is a vehicle that has considerable flexibility in its configuration which will allow it to be used beyond the FLAVIIR programme.

ACKNOWLEDGEMENTS

The authors acknowledge the technical and financial support for the project from BAE SYSTEMS and the EPSRC (grant number GR/S71552/01). They would also like to acknowledge the significant contributions made by many people, including: BAE SYSTEMS – Professor; Clyde Warsop, Mr M Pearson, Miss Philippa Wilson; Manchester University – Mr Paul Wilde; Cranfield University – Dr Giuliano Allegri, Dr Ali Savvaris, Miss A Buonanno, Mr A Clarke, Professor Phil John, Dr Craig Lawson, Dr Rui Pires, Mr P Mavidis, Mr S Mistry, Mr G Monterzino, Mr Barry Walker, Mr J Hurley, Mr G Muir.

REFERENCES

1 **Fielding, J. P.** and **Smith, H.** FLAVIIR an innovative university/industry research program for collaborative research and demonstration of UAV technologies. In Proceedings of the 25th International Congress of the Aeronautical Sciences, ICAS 2006, Hamburg, Germany, September 2006.

2 Large Model Association. Over 20KG scheme. Available from http://largemodelassociation.com/over20kg.htm.

3 **Yarf-Abbasi, A.** and **Fielding, J. P.** Design integration of the eclipse and demon demonstrator UAVs. In Proceedings of the Seventh AIAA Aviation Technology, Integration and Operations Conference (ATIO), Belfast, UK, 18–20 September 2007, AIAA paper 2007-7725.

4 **Yarf-Abbasi, A., Clarke, A., Lawson, C. P.,** and **Fielding, J. P.** Demon demonstrator UAVs. In Proceedings of the 26th International Congress of the Aeronautical Sciences, ICAS 2008, Anchorage, Alaska, September 2008.

APPENDIX

Notation

ACG	the ACG Company – supplier of composite materials
AMT	AMT Company, producer of the Olympus and Titan engines
APU	auxiliary power unit
CC	circulation control
CCD	circulation control device
CFC	carbon fibre composite
CNC	computer numerically controlled
ECU	engine control unit
EPSRC	Engineering and Physical Sciences Research Council
FCS	flight control system
FEP	fluorinated ethylene propylene
FTV	fluidic trust vectoring
GPS	global positioning system
MTOW	maximum take-off weight
UAV	unmanned air vehicle
UCAV	unmanned combat air vehicle